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DESIGN FOR A MOORE NO. 1 1/2 LATHE

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To increase our capability to machine small spherical parts, we are designing an ultraprecision lathe based on a Moore No. 1 1/2 measuring machine. The machine is being designed for single axis cutting, utilizing an accurate rotary table for spherical cuts. This report summarizes the design and presents an error budget analysis for the design.

Introduction

Various research projects at the Los Alamos National Laboratory require small spherical and hemispherical parts. We have in the past machined spherical surfaces by swinging single point tools with rotary motions mounted on conventional lathes, and in more recent years we have used both tracer lathes and NC machines to generate spherical surfaces. Although the addition to our shop during the past year of two CNC ultraprecision lathes* has greatly increased our capability of machining small hemispherical parts, we have a need for a machine dedicated to making hemispherical parts up to about 2 inch-diameter with high accuracy and good surface finish.

To fulfill this need, we investigated using a Moore No. 1 1/2 measuring machine as a base to build a small lathe. This report summarizes our preliminary design of this lathe, which we plan to build in FY82.

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*Previous IMOG reports have described our Moore No. 5 lathe and Pneumo MSG-325 lathe; Minutes of the 1980 Spring Meeting and the 1980 Fall Meeting, Machine Tool Subgroup of IMOG.

This lathe is designed for both diamond turning and conventional tool turning of spherical parts, by swinging the tool with an accurate rotary motion, not contouring. It is not intended for production work, because we require the lathe to be easily adapted to different sizes and economically make only one part of any given size. The design is unique in that we have placed the work holding spindle on the rotary table instead of the more conventional situation of the tool post on the rotary table. This configuration provides several advantages for our type parts.

The error analysis for this design predicts that parts with surface finishes of 2 to 3 microinch peak-to-valley and shape accuracies to within about 50 to 75 microinches can be made with a machine built to our preliminary design.

Requirements and Design Criteria

One of the standard methods of making small hemispherical shells is to machine a mandrel which the shell material can be plated or coated onto, then the outside of the shell is machined after relocating the mandrel accurately in the lathe spindle, and finally the mandrel is removed or leached out to leave a complete hemishell. The method is illustrated in Fig. 1. We think these mandrels and subsequent turning of the outside of shells will be the main type of part required on this new lathe.

In preliminary discussions we have considered two different basic types of machines, (1.) a rotary table generated radius, and (2.) a two-axis contouring machine. A description and comparison of these two types is presented in Fig. 2.

We thought we could utilize the Moore No. 1 1/2 machine effectively in a rotary table type machine -- from our experience with a Moore No. 3 plain way machine we knew of difficulties trying to make a contouring machine with this type base. Therefore, with the No. 1 1/2 base available, the most economical means of obtaining a machine to meet our needs is to build a machine with a rotary table to do single axis spherical cuts.

Also with the Pneumo Lathe available to make non-spherical parts by two axis contouring, limiting this new design to only spherical parts seems reasonable.

For spherical ended mandrel type parts, possibly the simplest machine would consist of a workpiece spindle and a perpendicular rotary table or spindle holding a tool bit. The type part which could be produced is shown as Type 1 of Fig. 3. If an encoder, indicator, or stop is added such that the table goes through exactly 90°, then a Type 2 part could be made. The Type 3 and 4 parts shown would require the addition of one or two slides. These slides would have to have smooth straight motion, and to put a shoulder in the right spot, the slides would also have to have high accuracy positioning capability.

With a light variation from a normal lathe configuration, putting the work piece spindle on the rotary table instead of the tool, a part like Type 5 of Fig. 3 can be made without additional accurate slides. To produce a fully contoured part, like Type 6, a two-axis contouring machine or a controlled radial axis mounted on the rotary table must be used.

For most of the work we anticipate for this machine the Type 4 configuration is adequate, although we have developed our preliminary design such that a Type 5 part can be made.

Measuring Machine Base

Even after deciding a contouring machine was not required, the machine tool requirements for both very high accuracy and rapid set-up for different size parts, led us to a conclusion that an accurate x-y motion base is essential. Although cuts will be made with only the rotary table or one slide at a time, repeatable and accurate positioning slides are needed; therefore, the Moore No. 1 1/2 measuring machine is a good choice for a lathe base.

The machine has 9 by 14 inch travel and a stacked slide configuration. The small size machine was attractive, because we intend the machine for very sm parts, and the smaller machine will allow the machinist closer access to the work zone. The overall size of the machine can be seen in the photograph, Fig. 4. A summary of the Moore No. 1 1/2 Measuring Machine standard specifications is shown in Table I.

Machine Configuration

The standard configuration lathe could be made by removing the column from the No. 1 1/2 and mounting an air-bearing spindle in its place, which has been done on many No. 3 bases. For this lathe we plan to use a different configuration.

This design is to mount a Moore Ultra-precise Rotary Table on the measuring machine work table and mount a tool post on the side of the vertical column, leaving the column with its measuring machine spindle in place. On top of the rotary table we will mount a small work holding spindle (4-inch Blockhead) with integral drive motor.

This configuration has the following advantages:

1. Conical parts can be cut, like Type 5 of Fig. 3.
2. The part can be moved to different work stations.
   For example, with the measuring machine spindle still in place, a part could be swept for radius accuracy by moving the work spindle from the tool post area to directly under the measuring machine spindle. Also, the measuring machine spindle could be used for drilling small holes in a part still held in the work holding spindle.

This machine configuration also has some disadvantages, for example:

1. The air and vacuum hoses for the spindle and the spindle drive power cable must be moved along with the rotary table during a cut.
2. The machinist may be behind the spindle and have a hard time seeing the total cutting process.

We think the disadvantages can be overcome with good design of hose and cable hook-ups, and use of a TV-microscope system; therefore, we are proceeding with the basic configuration of the work spindle mounted to the rotary table.

Other systems being planned for this small lathe are:

1. an HP-5501 laser interferometer for positioning read out,
2. servo motors for the axis drives,
3. a vibration isolation mount,
4. a tool post with necessary adjustments,
5. a tool set station, and
6. the slides between the rotary table and spindle for adjusting the radius of the part.

<u>Error Budget Analysis</u>

As Bob Donaldson states in his discussion of "Error Budgets" in the MTTF Report*, error budgets can be used for either evaluating a design to see if it meets a given set of specifications, or they can be used to estimate how accurately a part can be made by a certain machine design. An analysis

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*Robert R. Donaldson, "Error Budgets," in <u>Technology of Machine Tools</u>, Vol. 5, Lawrence Livermore National Laboratory, UCRL-52960-5, Chap. 9.14.

of errors in our design was undertaken for the second reason -- we don't have a specific tolerance to work toward, but simply a requirement to make perfect parts.

Both surface finish and shape or size errors were considered for this analysis. The errors were broken into two different principle directions, circumferential and polar, which are defined in Fig. 5.

The surface finish errors considered are listed in Table 2. The values of these errors are based on experience with our other machines, calculations, or published information. In general, there is no way to know if all errors are included, and some values are simply estimated; however, the preparation of such a list is a valuable design aid, because it points out possible trouble areas. Because not all errors occur at the same time or place, Donaldson suggests that the square root of the sum of the squares be used to combine the various contributions to the overall error. Using this method an estimate of surface finish of about 2 microinches peak-to-valley in the equatorial direction and about 3.3 in the polar direction are obtained.

In a similar manner, the shape error budget was considered as is shown in Table III. The largest effect on the sphericity of parts might be the rotary table runout and the repeatability of the rotary table position. Both of these items are being carefully considered in the design; for example, we have done some preliminary work on using a 10-inch Blockhead spindle for a rotary table which may provide better rotary motion than the Moore table used in the error analysis. Also the positioning values are based on using the Moore lead screws and encoder, and the laser readout may improve that.

The part diameter errors are considered in Table IV along with estimates of two other probable defects -- the center defect and a discontinuity at the transition point from rotary to linear motion.

In summary, this error budget analysis suggests we can make parts within 50 to 75 microinch in roundness and size, with surface finishes on the order of 3 microinches peak-to-valley roughness.

Simulated Machine Configuration

To acquire some practical experience with the type of configuration being considered for the Moore No. 1 1/2 lathe, we simulated this machine by mounting a 4-inch Blockhead spindle and drive on the rotary table of our Moore No. 3 ultraprecision lathe. This configuration is shown in Fig. 6. A tool post was mounted on the face plate of the regular spindle which is locked in place.

A test part was made using this configuration and compared to a similar part machined on our Pneumo lathe by two axis contouring. The two test brass parts are shown in Fig. 7, and their surface finishes are compared in Fig. 8 and Fig. 9.

In general, both parts are high quality ultraprecision parts. The part machined on the Moore No. 3 with a single axis cut has a slightly better surface finish, however, this single axis cut part had a slight defect (about 5 microinch) at the transition from the spherical to conical section which was not seen in the Pneumo two-axis contoured part.

Conclusion

The error budget analysis and other preliminary design work indicates the Moore No. 1 1/2 measuring machine will make an effective ultraprecision lathe. We are continuing our design efforts and plan to start work on modifying the measuring machine in early FY82.

Acknowledgements

The author would like to acknowledge the contributions to this project by Erich Baumgartner and George Zakar in machining the sample parts, Don Pasieka and Tom Novak in measuring the parts, and Bob Ansley in preparing the figures for this report and the drawing of several Moore No. 1 1/2 layouts.

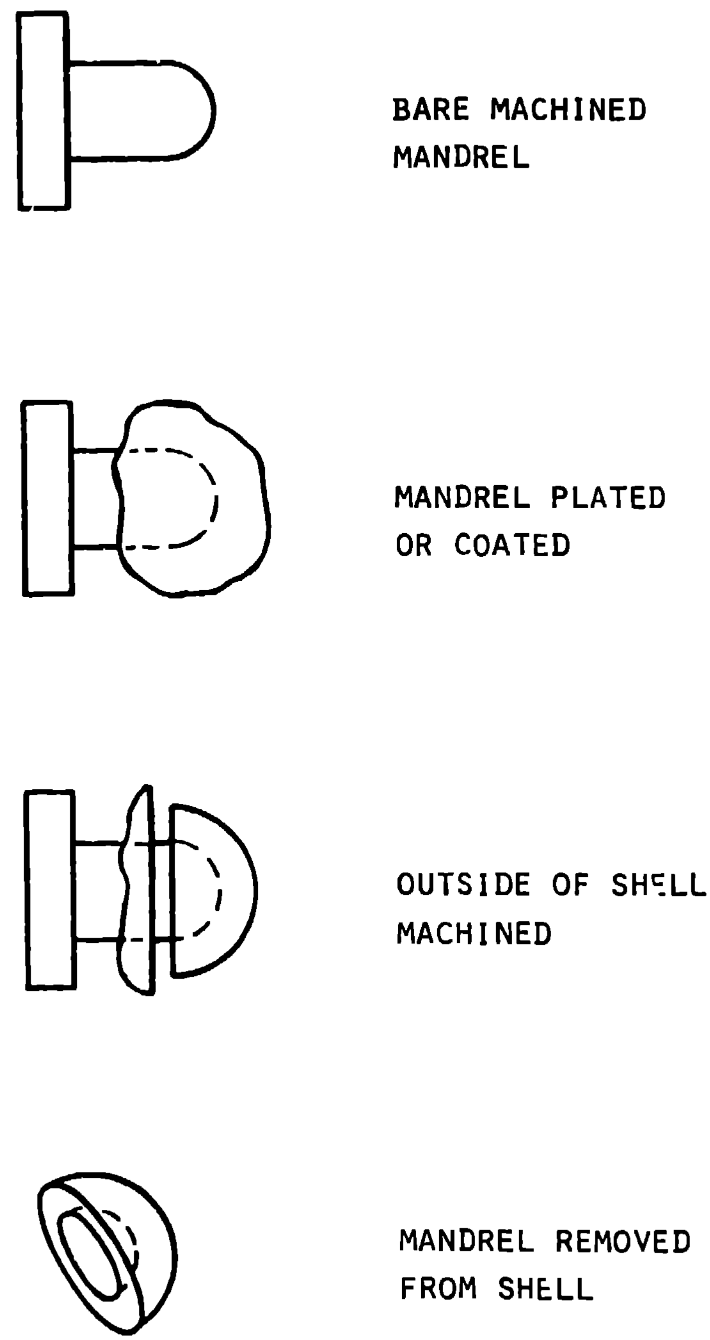
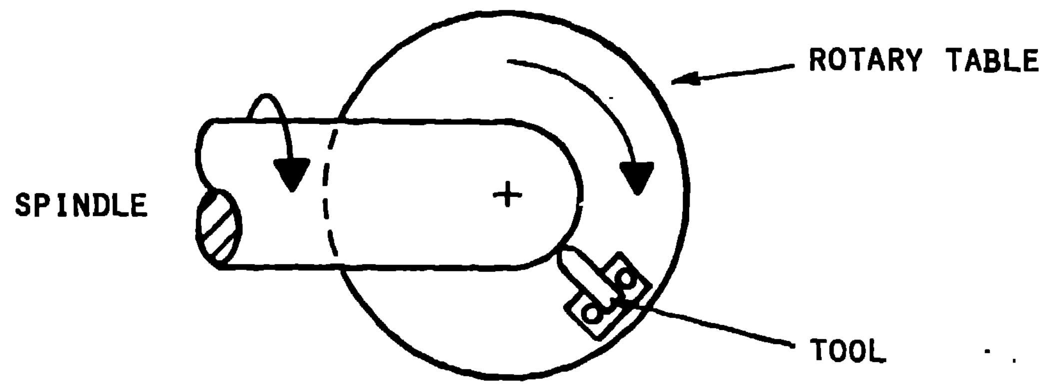


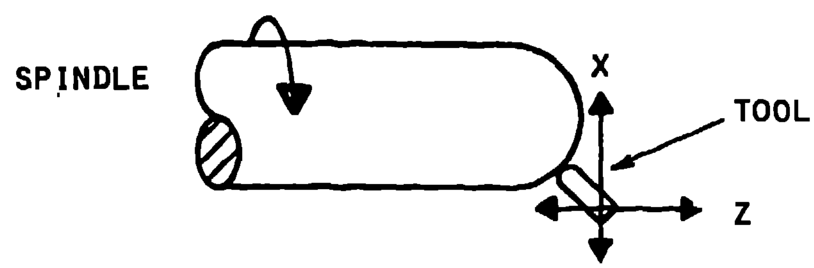
Fig. 1. Fabricating Shells by the Removable Mandrel Technique

ROTARY TABLE MACHINE



- SINGLE AXIS CUT
- ROTARY TABLE HAS TO BE GOOD, AND IN THE RIGHT LOCATION
- ONLY ONE POINT OF TOOL NEEDS TO BE GOOD

CONTOURING MACHINE



- TWO AXIS CUT
- BOTH SLIDES MUST HAVE GOOD CONTROL
- TOOL HAS TO HAVE GOOD, KNOWN RADIUS

Fig. 2. Comparison of Methods to Generate Spherical Shapes

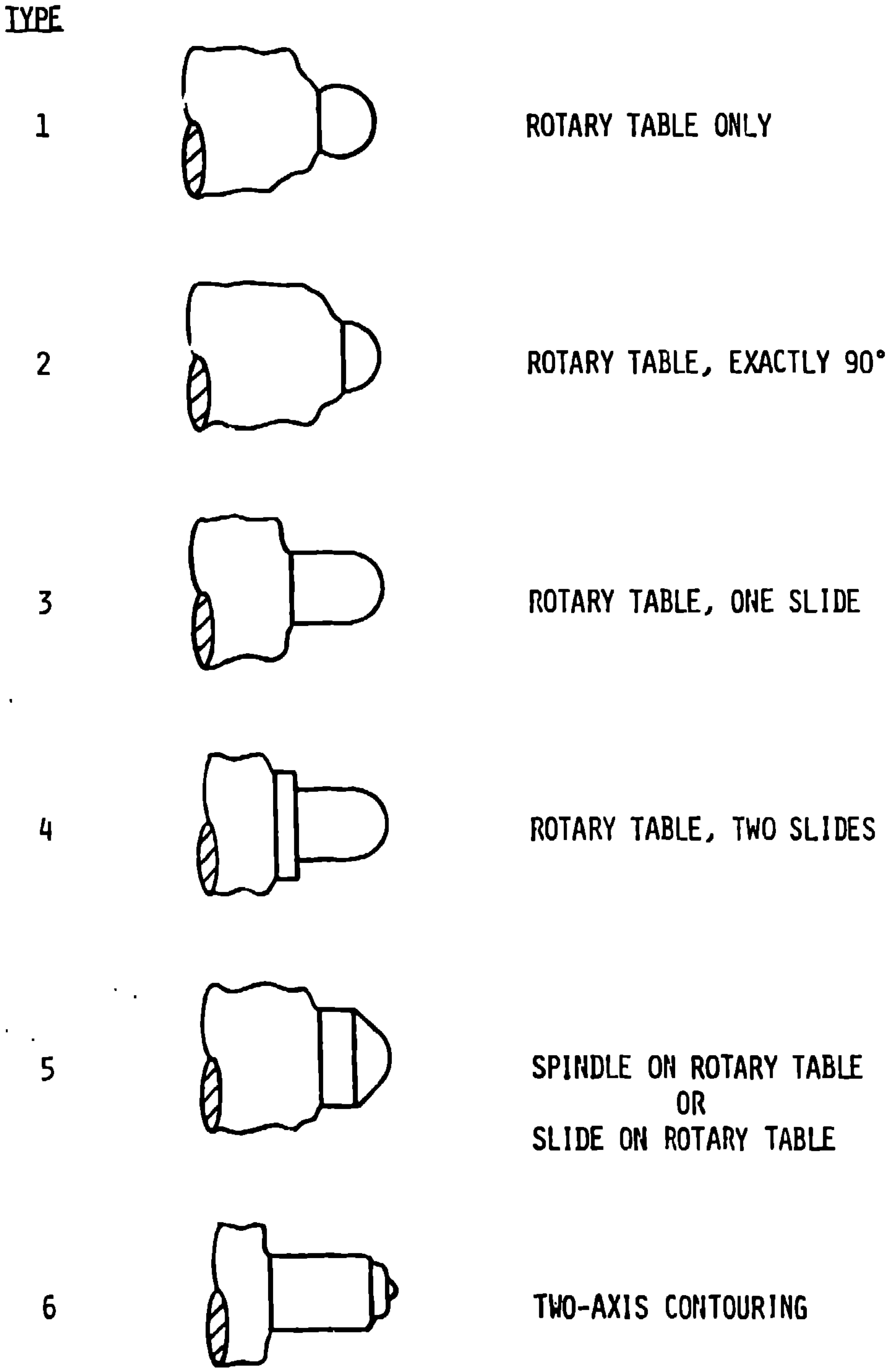


Fig. 3. Types of Machined Mandrels

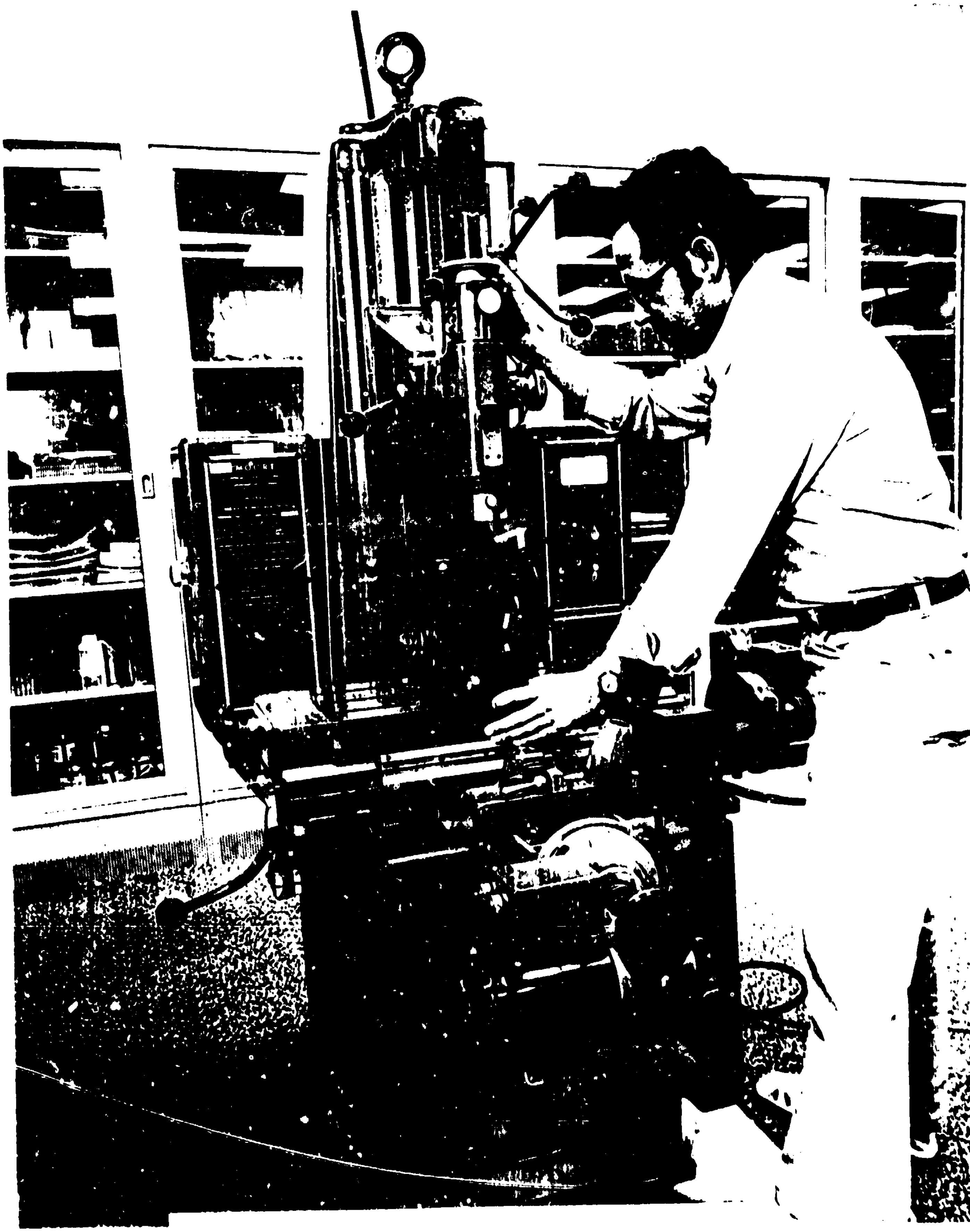


Fig. 4. Moo~e No. 1 1/2 Measuring Machine

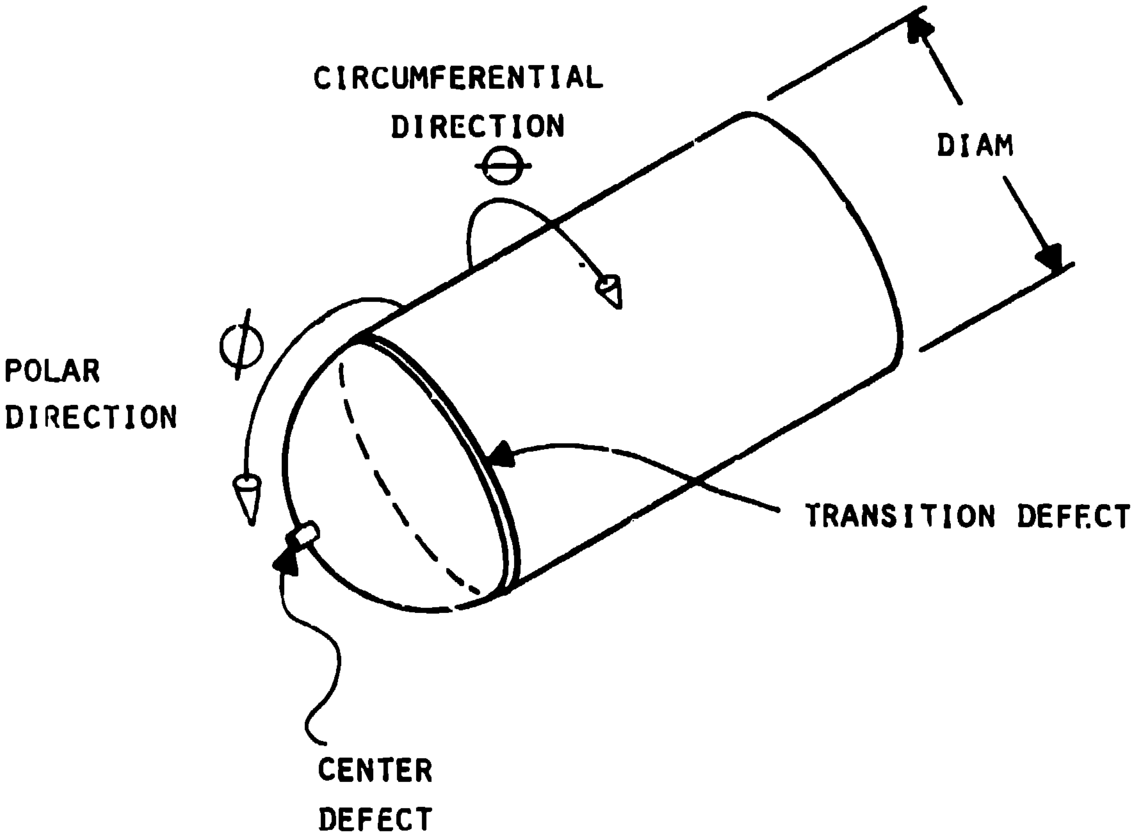


Fig. 5. Types of Errors Considered

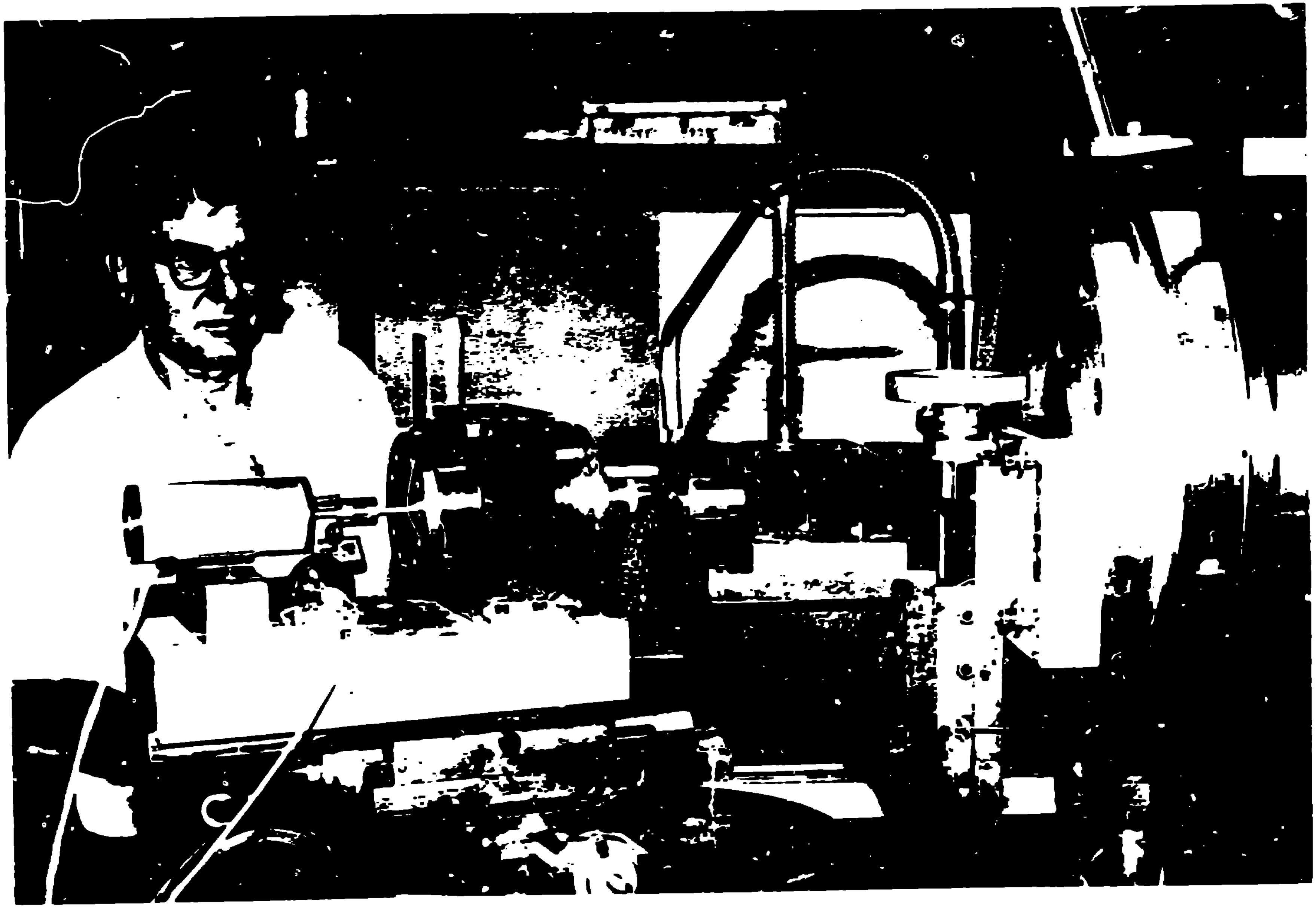


Fig. 6. Work Spindle on Rotary Table

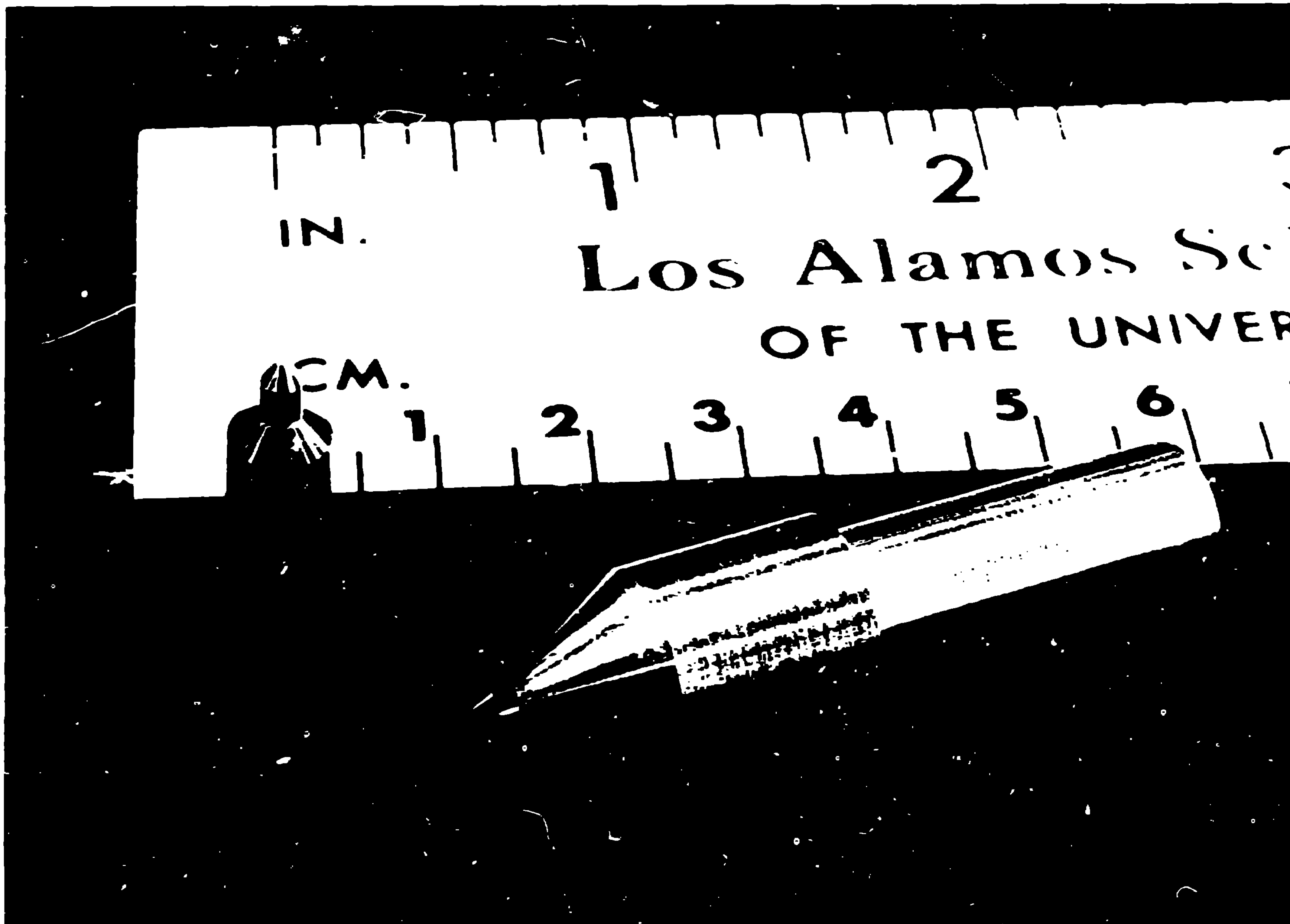
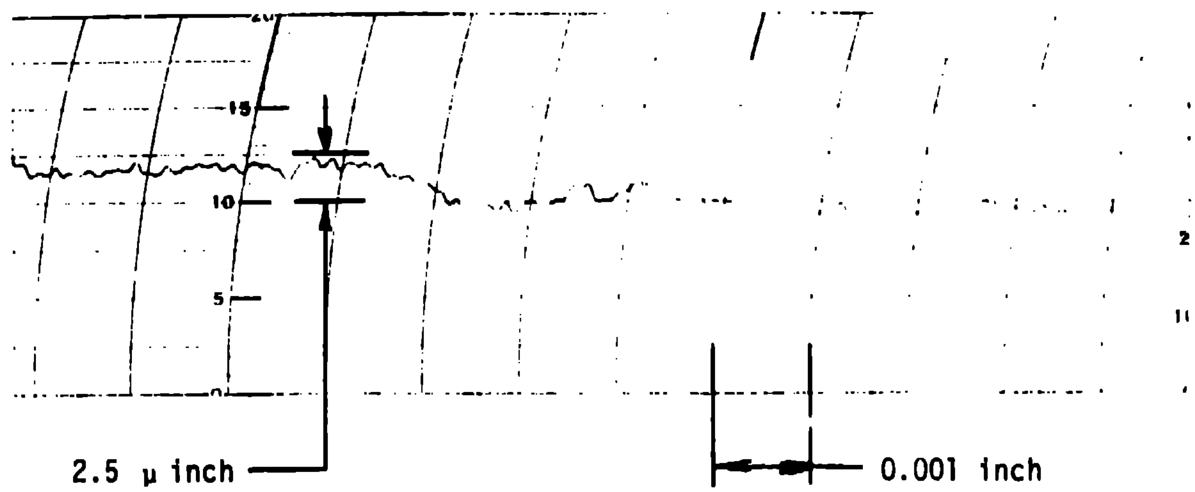
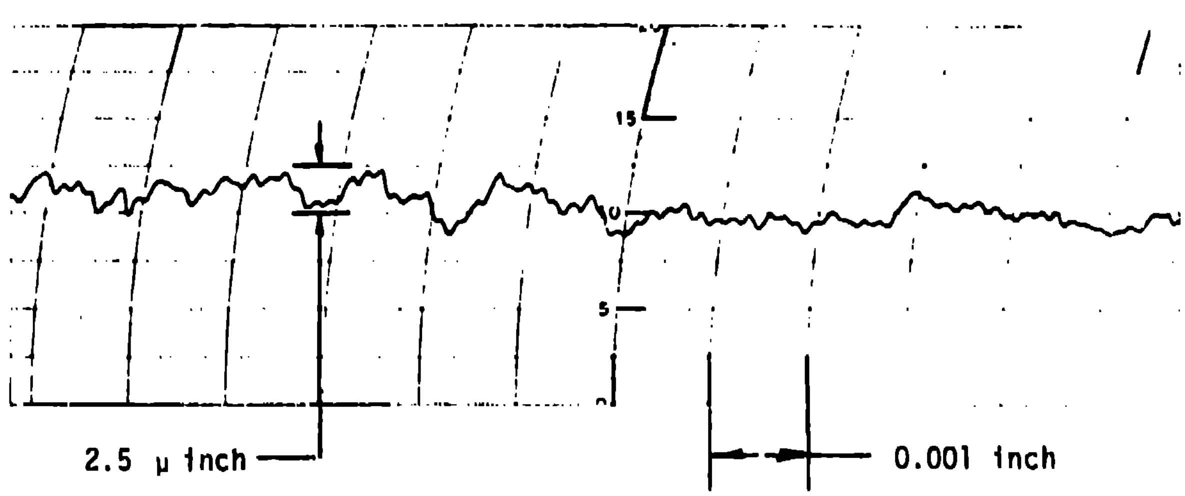


Fig. 7. Brass Test Pieces



SINGLE AXIS CUT

Fig. 8. Surface Finish of Part Machined on Moore No. 3



CONTOURED CUT

Fig. 9. Surface Finish of Part Machined on Pneumo Lathe

TABLE I

MOORE NO. 1 1/2 MEASURING MACHINE SPECIFICATIONS

* POSITIONING ACCURACY

  X AND Y, 35 MICROINCH FULL TRAVEL

  GREATEST ERROR IN ANY ONE INCH
  15 MICROINCH

* STRAIGHTNESS

  LONGITUDINAL (BOTH PLANES), 25 MICROINCH

  CROSS SLIDE (BOTH PLANES), 15 MICROINCH

* SQUARENESS

  0.4 ARC SEC

* SPINDLE ACCURACY

  TRUENESS OF ROTATION, 5 MICROINCH TIR

TABLE II

SURFACE FINISH ERROR BUDGET

ERROR SOURCE	ESTIMATED AMPLITUDE (MICROINCH P-V)	
	θ DIR	Ø DIR
TOOL RAD.-THEORETICAL FINISH	-	0.5
TOOL EDGE QUALITY	-	1.0
TOOL EDGE SHARPNESS-CUTTING MECH.	1.0	-
FLOOR VIBRATIONS	0.5	1.5
AIR BORNE NOISE	0.2	0.2
SPINDLE RANDOM MOTION	0.5	0.5
SPINDLE DRIVE INFLUENCE	1.0	0.5
AIR PRESSURE FLUCTUATIONS	0.3	0.3
SLIDE OR ROTARY TABLE ROUGHNESS	0.5	2.0
SLIDE DRIVE INFLUENCE	1.0	1.5
MATERIAL PROBLEMS	0.5	0.5
TOTALS	5.5	8.5
$\sqrt{\Sigma x^2}$	2.03	3.26

TABLE III

SHAPE ERROR BUDGET

ERROR SOURCE	ERROR (MICROINCH)	
	θ DIR	$\emptyset$ DIR
ROTARY TABLE ROUNDNESS	-	15
ROTARY TABLE POSITION	-	20
TEMPERATURE CHANGES	-	5
SPINDLE RUN OUT	5.0	-
SPINDLE DRIVE	1.0	-
SPINDLE BALANCE	0.5	-
SPINDLE GROWTH	-	~ 10
TOOL WEAR	-	0.1
FIXTURING	~ 10	~ 10
MATERIAL	~ 5	~ 5
TOTAL	21.5	65.1
$\sqrt{\Sigma x^2}$	12	29.6

TABLE IV

RADIUS OR DIAM ERROR

ERROR SOURCE	POSSIBLE ERROR (MICROINCH)
RADIUS SET	25
METROLOGY OF TEST PIECE	10
TEMPERATURE CHANGES	50
SPINDLE GROWTH	10
CONTROL OR POSITION	20
TOTAL	115
$\sqrt{\Sigma x^2}$	61

CENTER DEFECT

20 MICROINCH DIAM X 20 MICROINCH HEIGHT

TRANSITION DEFECT

LESS THAN 5 MICROINCH